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ARAPAIMA is a proximity operations mission sponsored by the US Air Force Office of Scientific Research (AFOSR) and the Air Force Research Laboratory (AFRL), to perform the in-orbit demonstration of autonomous proximity operations for visible, infrared, and point cloud generation of resident space objects (RSOs) from a nanosat platform. The nanosat is of the 6U CubeSat class, with overall dimensions of 12x24x36cm, a mass of 9.78kg, and has been selected as part of AFRL's University NanoSat Program (UNP) Cycle 8. This paper describes the mission goals, concept of operations, science objectives and subsystem design and selection, with focus given to a detailed mission analysis and the requirements flow-down.

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Application for RSO Automated Proximity Analysis and IMAging (ARAPAIMA): Development of a Nanosat-based Space Situational Awareness Mission

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ABSTRACT

ARAPAIMA is a proximity operations mission sponsored by the US Air Force Office of Scientific Research (AFOSR) and the Air Force Research Laboratory (AFRL), to perform the in-orbit demonstration of autonomous proximity operations for visible, infrared, and point cloud generation of resident space objects (RSOs) from a nanosat platform. The nanosat is of the 6U CubeSat class, with overall dimensions of 12x24x36cm, a mass of 9.78kg, and has been selected as part of AFRL's University NanoSat Program (UNP) Cycle 8. This paper describes the mission goals, concept of operations, science objectives and subsystem design and selection, with focus given to a detailed mission analysis and the requirements flow-down.

By demonstrating robust, affordable, and responsive rendezvous and proximity operations of a nanosat with an uncooperative RSO, successful completion of the ARAPAIMA mission will validate a range of technologies for space-based space 12situational awareness (SSA) and debris removal from Low Earth Orbit (LEO).In addition, the mission will validate a set of key technologies and their integration at system level, such as miniaturized commercially available sensors, a miniaturized warm gas propulsion system for CubeSat applications, as well as advanced relative navigation and proximity operations algorithms implemented on a nanosat.

MISSION OPERATIONS CONCEPT/OVERVIEW

ARAPAIMA stands for "Application for RSO Autonomous Proximity Analysis and IMAging". ARAPAIMA is a proximity operations mission sponsored by the US Air Force Office of Scientific Research (AFOSR) and the Air Force Research Laboratory (AFRL), through the University Nanosat Program, to perform the in-orbit demonstration of autonomous proximity operations for visible, infrared, and three dimensional imaging of resident space objects (RSOs) on a cubesat platform.

The payload consists of a commercially available infrared (IR) camera and a miniature laser rangefinder (LRF) with a range of a few km. The instruments are installed on the cubesat so that their optical axes are pointing in the same direction. The cubesat is equipped with a warm gas propulsion system which enables it to perform orbital maneuvering and reaction control of attitude. The goal of the ARAPAIMA mission is to perform the in-orbit demonstration of autonomous proximity operations for visible, infrared, and three dimensional imaging of RSOs. ARAPAIMA is of the

6U cubesat class with overall dimensions of 12x24x36cm. The ARAPAIMA cubesat can be seen in Figure 1.
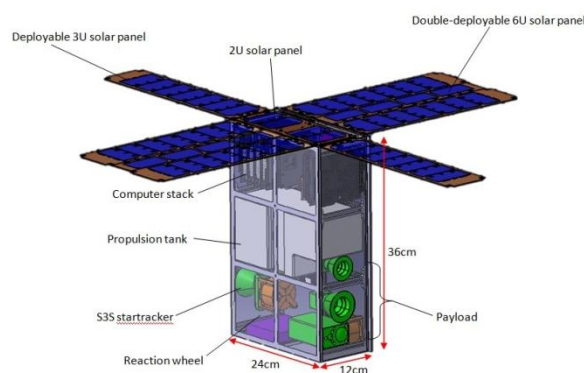

Figure 1: CAD model of the ARAPAIMA Cubesat

Mission Concept of Operations

The in-orbit operations of ARAPAIMA and specific proximity operation scenarios can be broken down into five steps. Each of the five mission steps is tied-in with

an objective of increasing complexity and science returns. The mission concept of operations (ConOps) can be seen in Figure 2. This figure shows a "cartoonized" and simplified outline of the ARAPAIMA mission.
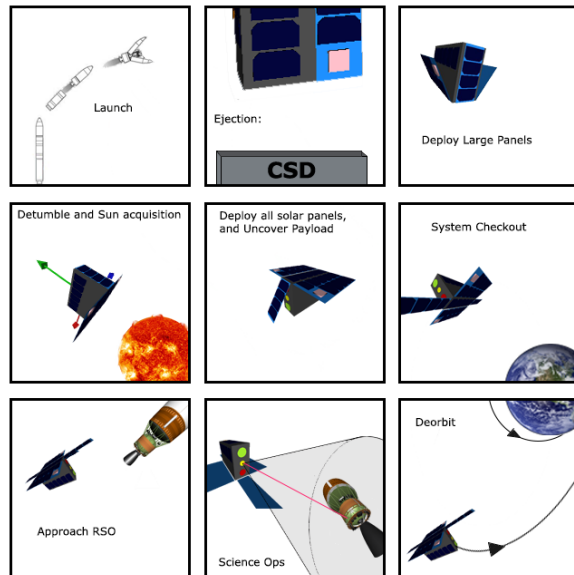

Figure 2: ARAPAIMA Concept of Operations

Achievement of each objective, within selected tolerances, clears the mission to proceed to the next step. At the completion of each step the cubesat enters a "telecom mode" in which the attitude is commanded so that the antennas of the communications subsystem point in the nadir direction. The ground control team verifies successful completion of each step and downloads the data products generated during the step, including the house keeping data. Once the ground control team verifies the successful completion of the step it issues an authorization to precede (ATP) command to the cubesat. While deorbiting the cubesat is left out of the mission objectives; it is a critical objective for a fully successful mission. Simulations for mission planning will take into account that propellant should be allocated for a deorbiting maneuver. The mission is considered successful after the cubesat reenters the atmosphere and disintegrates.

Science Concepts of Operation

The ConOps for ARAPAIMA science is illustrated in Figure 3. Extensive guidance, navigation and computer vision algorithm development will be needed to ensure mission success.
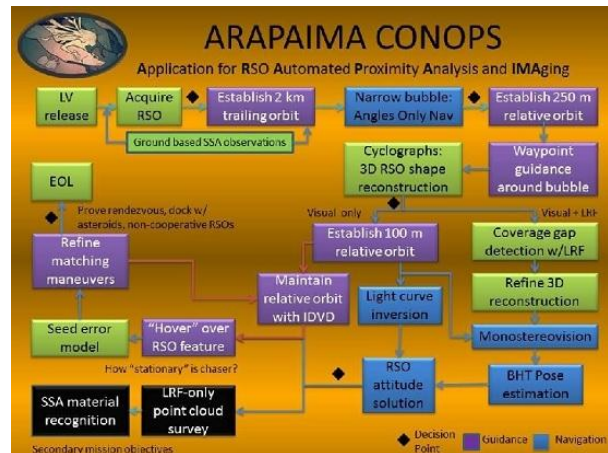

Figure 3: ARAPAIMA Science ConOps

The science ConOps shows a almost step-by-step recreation of the mission from a science point-of-view. It demonstrates the many successes that must take place in order to ensure mission success. Among these successes are many new technologies and methods.

PROGRAM SCOPE/MISSION OBJECTIVES

Mission Objectives

1. Determine the 3-D shape of the RSO without previous knowledge.
2. Autonomously navigate and safely maneuver in close proximity to the RSO, in low earth orbit.
3. Estimate the attitude state of the RSO by remote observation.

The mission objectives are achieved in five steps of increasing complexity. During the first two steps the cubesat is commanded by ground control to maneuver within LRF range of the RSO and acquire a relative circular orbit with respect to it. The third step consists of ARAPAIMA maneuvering autonomously to reduce the size of the relative orbit to a few hundred meters by applying Angles Only Navigation (AON) techniques. The fourth step will perform visible and IR passive imaging of the RSO. During the fifth step a combination of chaser attitude motion and relative motion between the cubesat and the RSO is employed to perform 3D imaging of the RSO by combining LRF measurements and knowledge of the cubesat inertial attitude and position. Successful completion of the mission validates a range of technologies that can be used for debris removal from low Earth orbit by demonstrating robust, affordable, and responsive rendezvous of cubesats with uncooperative RSOs, on a budget two orders of magnitude lower than previous observer missions such as XSS-11 (AFRL) and Orbital Express (DARPA).

Mission Success Criteria

It is the decision of the team with close guidance by the University Nanosatellite Program (UNP) Program Office (PO) to not only define the full and minimum success criteria, but also the extended success criteria. This allows for achievable minimum and full success, while also correctly portraying the mission and the mission goals as a whole.

1. Minimum mission success is achieved by successfully taking an unresolved image of the RSO and downlink it to the ground station
2. Full mission success is defined by the statement:
   Maneuver the nanosat into the proximity of the RSO with commands generated by the mission operators, and take an image in which the RSO occupies at least 15\% of the pixels of the visible and IR spectrum cameras
3. Extended mission success is achieved by meeting the following criteria:
   On-board planning and execution of maneuvers to acquire a relative orbit with respect to the RSO and use range measurements to generate a 3D point cloud

Mission Phases

1) Maneuver within LRF range (less than 2km) from the RSO using pre-loaded commands: After separation from the launcher, detumbling, and systems check, ARAPAIMA is authorized to perform the first step. During this step, the cubesat approaches the RSO to a distance just below 2km. The cubesat is commanded to point the payload at the RSO and take visible and IR images and LRF ranges to confirm the successful execution of the step. 2) Acquire a relative circular orbit, with respect to the RSO, of less than 2km radius using pre-loaded commands: Once the verification of the relative distance is completed, an ATP from the ground station is issued, and the cubesat uses pre-loaded commands to acquire a circular relative orbit with the RSO. The radius of relative orbit is within LRF range, and similarly to the first step, after completion of the maneuvers the cubesat uses its cameras for RSO imaging and the LRF to confirm its range. Additionally, the attitude is commanded so that the payload tracks the RSO as ARAPAIMA orbits it. The ground control team issues an ATP after confirmation of relative orbit acquisition, and the cubesat proceeds to the next step. 3) Maneuver autonomously to reduce the size of the relative orbit to below a few hundred meters: The third step starts with the cubesat acquiring the RSO with its visible and IR cameras and using the LRF to perform periodic ranging. The orbits of both the RSO and the cubesat are propagated on board the cubesat, and a

propellant optimal maneuver is computed to take the cubesat into a tighter relative circular orbit. During the inactive, nonthrusting arcs of the reconfiguration trajectory the cubesat periodically acquires the RSO with the cameras, and it takes LRF measurements and GPS solutions to verify the accuracy of the OMT maneuvers and ensure operational safety. Operations during the third step are defined as autonomous because the orbital and attitude maneuver commands are generated on board the cubesat instead of being pre-loaded by ground control. The team emphasizes that the autonomous maneuvers performed during the proximity operations will be designed for simplicity and robustness. The maneuvers will be fully validated on a high fidelity real-time mission simulation test-bed throughout the lifetime of the mission during preparatory sessions. At the end of the third step, the cubesat lies in a circular orbit of 250m diameter relative to the RSO. 4) Perform autonomous visible and IR imaging and LRF reflectivity measurements of the RSO: After successful completion of the third step and receiving the ATP, the cubesat proceeds with the fourth step during which it is tasked to perform autonomous imaging of the RSO and to autonomously plan relative orbit maintenance maneuvers to offset the effects of differential drag, J2, and solar radiation pressure (SRP). Images taken in the visible and IR spectra will be used by the team to inspect the RSO and determine any outstanding features. Once a certain number of observations are made, the cubesat enters its telecom mode to download the data to the ground station. Upon analysis of the imaging data, the ground control team decides to issue the ATP to the fifth step. 5) Perform 3D imaging of the RSO using a combination of attitude motion and relative motion, with respect to the RSO, and combine LRF measurements and knowledge of the cubesat's inertial attitude and position to generate point clouds. 5a) Open outer loop control of attitude: Pre-programmed attitude profiles are used, which command the cubesat to perform an up-and-down scanning motion or a slow spiral with respect to the RSO. A coarse attitude state of the RSO with respect to the chaser body frame can be estimated and transformed to an inertial frame based on the attitude solution of the chaser. Point clouds of larger resolution resolve the features of the RSO and can be used to determine their relative locations with respect to the chaser body frame. Based on the information extracted from the point clouds, RV and docking paths can be planned on-board, and the chaser is commanded to follow them up to a safe distance to the RSO. End-to-end simulations of the scanning phase of the mission will be employed to determine which parts are better performed autonomously and which are better performed by pre-loaded commanding. These methods are also applicable to 3D imaging of tumbling or maneuvering RSOs. 5b)

Closed outer loop control of attitude: The IR camera is used to capture images of the LRF bloom on the surface of the RSO and close the outer attitude control loop according to some coverage criterion. To close the outer attitude loop with the IR camera a three-part algorithm is employed to detect and close gaps in LRF strike point coverage on the RSO. Gap detection is achieved using Voronoi diagrams in which Voronoi cells are centered at the LRF strike points. Time stamped range measurements of each LRF strike point are registered to the image taken by IR camera. The implementation relies on the fact that an area of sparse or no coverage has one or more Voronoi points whose "empty circle," centered at the Voronoi point and containing no strike points is large relative to the other empty circles in the diagram. This enables the detection of a gap and its marking for every image that makes up the original spherical projection. The nearest detected gap on the projection of the path of the chaser on the RSO satellite is computed, and it is used to generate a slew command toward the center of the gap. The chaser triggers the LRF to cover the gap with strike points. Once the chaser "over flies" the gap, the map is updated with the new strike points, gaps are re-computed, and a new gap is prioritized for targeting.

Mission Operational Modes

The operational modes of the proposed payload are described in Figure 4. The operational modes can be thought of as states of a finite state machine (FSM), the nanosat. The nanosat is in only one state (mode) at a time and it can transition to another mode only if certain conditions are met.

Figure 4:ARAPAIMA Operational Modes

At this stage of the mission design, the operational modes are used to derive power budgets and data budgets. Towards the end of the preliminary design phase the operational modes defined here will be implemented in MATLAB/Simulink/Stateflow and will be used as a master mission script during simulations.

The team has also defined nominal and entry conditions and will commence working on off-nominal entry and exit transitions. A total of 11 modes have been defined and they are enumerated below. A snapshot of the operational modes table is presented in Figure 4 to show its structure. The operational modes are:

1. the P-POD store mode during which the nanosat is stored in the P-POD and awaiting launch - the nominal exit takes place when the P-POD door is open and the nanosat is released from the launcher;
2. the deployed mode during which the nanosat is tumbling after release from the P-POD – the solar panels are deployed after a certain amount of time and the mode is exited after the OBC is booted up;
3. the detumble mode during which the nanosat uses the rate gyros of the IMU and its RCS thrusters to cancel the angular rates about each axis – the mode is exited nominally if the angular rate about each axis has been brought below a certain threshold, the largest solar panel has been pointed towards the Sun, and the telecom antennas are pointing in the nadir direction;

4. the system check mode during which the OBC commands the nanosat subsystems to perform tasks with well understood and defined input-output relationships – the mode exits nominally upon ATP from ground control;

5. the ground control RSO approach mode during which the nanosat performs pre-loaded orbital maneuvers to approach the target and acquire relative orbit which respect to it – the mode is exited nominally upon termination of the orbital maneuver and ATP from ground station;

6. the science operations mode during which the nanosat performs visible and IR spectrum and 3D imaging of the RSO – the mode is exited nominally upon command from the OBC to perform relative orbit;

7. the relative orbit maintenance mode during which the nanosat performs pre-loaded orbital maneuvers to offset the effect of differential drag, J2, and SRP – the mode is exited nominally upon successful execution of the maneuvers and ATP from ground control;

8. the comms mode during which the nanosat is pointed such that the telecom antennas are in the nadir direction – the mode is exited nominally upon ATP from ground control;

9. the collision avoidance mode during which upon command from ground control or from the OBC the nanosat performs a separation maneuver – the mode is triggered by detection of anomalous orbital parameters of the nanosat which would put it on path that penetrates the safety sphere centered at the RSO – the mode is exited after ground control verifies the collision danger subsided and the issues an ATP;

10. the deorbit mode during which the nanosat lowers is perigee so that it will reenter the atmosphere and disintegrates – the mode does not have an exit but it ends when the nanosat has been confirmed reentered;

11. the safe mode is designed to protect the payload and nanosat subsystems – it is likely that in this mode the nanosat slowly spins about it major axis, the payload instruments point away from the Sun – the mode is exited upon ATP from ground control.

The modes have been kept under a dozen as this stage of the mission design. Later on, as the concept of operations mature, more modes will be added. For example, relative orbit maintenance and exit from the safe mode can be performed either with pre-loaded commands or autonomously. The modes table will be extended to include both types of modes.

CUSTOMERS

The mission already has six confirmed customers, three from each of the Air Force Research Laboratory (AFRL) Space Vehicles Directorate and from the NASA Goddard Space Flight Center. The customers are interested in either the data products, i.e., images and 3D point clouds of the RSO, or in testing algorithms on-board the nanosat.

AFRL

Dr. Brian Flewelling, AFRL/RVSV, is currently engaged in multiple aspects of space-based SSA. The images captured and downlinked by ARAPAIMA will be used in the AFRL/RVSV's Sensor-based Control of Relative Motion (SCReAM) laboratory to test and validate multi-resolution techniques in spacecraft characterization and relative pose determination.

Dr. Josue Munoz and Mr. Nathan Stastny,AFRL/RVES, provide support to the AFRL in simulations and military utility assessment of several ongoing and future flight missions. Their interest in the ARAPAIMA missions is focused on the on-orbit demonstration of guidance algorithms for inverse dynamics in the virtual domain (IDVD) and for angles only navigation (AON).

NASA Goddard

Mr. Thomas Flatley, Code 587, is the Branch Chief for the Science Data Processing Branch. Mr. Flatley and researchers in his branch are interested in the development of image processing algorithms for creating stereo vision with one camera and ranging with visual-only methods. Mr. Matt Strube and Mr. John van Eepoel, with the NASA Satellite Servicing Capabilities Office (SSCO), have confirmed their interest in using ARAPAIMA as a platform to gather relevant on-orbit data to benefit future rendezvous and proximity operations (RPO) missions such as the geostationary Earth orbit (GEO) based satellite servicing concept currently being developed by SSCO.

Collaboration with the SCReAM Lab

The Guidance Navigation and Control Group in the Spacecraft Component Technology Branch within the Space Vehicles Directorate of the Air Force Research Laboratory located at Kirtland Air Force Base in New Mexico administers the SCReAM Laboratory, which is involved with research in the areas of relative motion, image processing and computer vision, all of which fall squarely within the core science mission of ARAPAIMA. Collaboration would benefit both ARAPAIMA mission readiness as well as advance the existing research within AFRL/RV.

Two phases are proposed for collaboration with the SCReAM lab. The first is algorithm development, the second is Payload-in-the-Loop (PIL) testing. If the I\&T timeline allows for hardware completion prior to the January 2015 Flight Competition Review (FCR) for ARAPAIMA, the team would like to perform Hardware-in-the-Loop (HIL) testing in the SCReAM lab as well.

The primary point of contact for pre-algorithm development on ARAPAIMA would be Dr. Brien Flewelling, Research Aerospace Engineer with AFRL/RV and Director of the SCReAM lab. Pre-existing research by the author has set up initial proximity operations simulations for relative motion, as well as camera simulations of imaging with a Narrow Field of View (NFOV) camera. From initial discussions, several areas have been determined for collaboration and advancement of existing work.

The SCReAM lab has a full simulated star tracker catalog. Currently, all camera simulations involving the RSO (ARAPAIMA's upper stage) involve a dark background. Generating realistic star imagery and testing imaging algorithms will help with accurate simulations of initial RSO acquisition, Earth/Sun/Moon lighting/imagery constraints, etc.

The SCReAM lab is involved in relative-motion based computer vision problems, several of which will be encountered by the ARAPAIMA mission. Combining resources, with the understanding that code developed in the lab will remain part of the lab's repository, will allow for furthering the understanding of future students who collaborate with the lab.

Autonomous visual-only imaging and pose estimation will involve advanced feature detection and blending algorithms. In addition, the final phase of ARAPAIMA will select a "feature of interest", and determine the ability of the cubesat to maintain a relative orbit in reference to that feature for advanced study. Reflectance as a function of observer angle is another area that has not been studied yet for ARAPAIMA.

Currently, all images that are tested are created within the MATLAB simulation environment. Realistic images will help determine the actual performance of the flight camera, and prepare for full mission operations.

After the Preliminary Design Review, the team intends to make use of the SCReAM lab's Attitude Control System Proving Ground (ACS-PG) to perform payload-in-the-loop tests. Models of various representative RSOs will be created and mounted on the ACS-PG. The goal is for the ARAPAIMA payload of an IR camera and a Laser Rangefinder (LRF) representative, such as the X-Box Kinect, to be mounted in proximity to the ACS-PG.

Imaging algorithms will then be rigorously tested on a variety of relative motion scenarios, both in-plane and out-of-plane. The fidelity of the algorithms will be tested, and improvements suggested for operational use as applicable. As mentioned previously, if sufficient hardware integration has occurred by FCR, the team intends to use the Engineering Development Unit (EDU) of ARAPAIMA to the ACS-PG and further test the capabilities of the cubesat to perform its primary mission.

The primary user of the SCReAM lab would be Lt. Michael (Mikey) Nayak, who by virtue of being assigned to Kirtland Air Force Base, already has access to AFRL/RV facilities. The next step would be lab access for Lt. Nayak, to begin collaborative work on algorithm development. It is anticipated that other ARAPAIMA personnel do not require access to the SCReAM lab at this time.

However, during PIL testing, it is possible that certain ERAU students may wish to visit the lab, both to collaborate on the testing and to gain outreach with AFRL/RV. This is in line with the objectives of the University Nanosatellite Program (UNP) as well. Arrangements for these students will be made on a case-by-case basis through the proper channels in AFRL/RV.

SPACECRAFT OVERVIEW

Military Relevance

The primary ARAPAIMA mission objectives aim to explore and directly contribute to a broad range of next-generation U.S. national security objectives, including but not limited to space servicing, space diagnostics, space support and autonomous space operations. The mission's low-cost, agile cubesat platform plans to demonstrate key capabilities directly applicable to military interests, specifically in the areas of space superiority and space situational awareness, such as rendezvous and proximity operations, autonomous mission planning, integration of commercial off the shelf (COTS) parts for low-cost test and flight, as well as other enabling space technologies.

The ARAPAIMA mission addresses three of the Air Force 15 prioritized space capabilities:

1. Space Situational Awareness (#4): The mission is designed to perform space-based 3D imaging of unknown RSOs, thus enabling the

SSA capability to catalogue space systems from a space-based platform, as well as to track space debris.

2. Satellite Operations (#8): The concept of operations (CONOPS) requires a combination of autonomous and ground control operations to provide highly accurate maneuvering solutions for formation flying with the RSO, thus ARAPAIMA addresses the satellite operations capability.

3. Offensive Space Control (#10): The mission also enhances offensive space control capability through the novel imaging algorithms being developed. When combined with maneuvering and near-optimal path planning algorithms, this allows the maximum utilization of an agile microsatellite to negate an adversary's space capabilities.

Cubesat integration: The military utility of the ARAPAIMA mission can be derived from missions with similar objectives, such as XSS-102, XSS-113 (AFRL) and Orbital Express 4 (DARPA). In addition, the cubesat bus can be directly adapted to a variety of Department of Defense (DoD) science and engineering missions. The modular design leads to easy payload integration, for example, for space weather missions of interest to DoD and NASA, low-cost GPS, MILSATCOM, and DSP gap-fillers.

Long-term impacts to military missions include a continued reduction in satellite size, a decrease in launch costs due to the added capability for lesser mass, and an extension of the capabilities of future space missions.

Orbital debris removal and asteroid exploration: The technologies being developed, integrated, and tested on ARAPAIMA are also directly applicable to the field of orbital debris removal. ARAPAIMA 3D imaging and state estimation algorithms can be employed in collusion with algorithms already developed by other researchers to plan the maneuvers for imaging and autonomous docking with a tumbling asteroid. Laser range finder algorithms developed for ARAPAIMA are applicable to measuring surface characteristics and topography mapping for small satellite asteroid missions. Other applications of ARAPAIMA technology include the SeeMe project (DARPA).

Lessons learned from low-cost, low-risk integration and test will be documented and transferred to the operational community, such as AFSPC/A3, to facilitate development of future CONOPS, missions and systems.

Active Orbital Debris Removal in Low Earth Orbit

Orbital debris designates all of the man-made objects in Earth orbit which no longer serve a useful purpose, e.g., inactive spacecraft, upper stages of launch vehicles, material released intentionally or unintentionally during stage separation, and material resulting from upper stage or satellite explosions and collisions. Orbital debris is found in orbits ranging from low Earth orbits (LEO) to geostationary Earth orbits (GEO). The range with the largest density of debris spans the LEOs from about 500km to 1000km altitude. Recent events, such as the Chinese antisatellite test of 11 January 2007 and the collision between the active Iridium 33 (US) satellite and the decommissioned Cosmos 2251 (FSU) on 10 February 2009, have increased the total number of objects, including active satellites and debris, by 125% within the 500-1000km altitude band. The danger that orbital debris poses to active satellites and the crew of the International Space Station (ISS) is obvious, as demonstrated by the collision of 2009 and by the fact that within a year, from April 2011 to March 2012, the ISS crew and operators had to deal with six orbital debris events, four which resulted in ISS performing collision avoidance maneuvers and two which resulted in the crew retreating to the Soyuz capsules due to the lack of time to perform collision avoidance maneuvers.

To address the increasing danger posed by orbital debris two types of measures are already implemented or are planned for implementation 1) mitigation and 2) remediation. Mitigation of orbital debris consists of procedures to safely re-enter a LEO satellite or upper stage within 25 years at the end of mission, aka the 25-year rule, or to move GEO satellites in "graveyard" orbits. According to Liou, mediation activities on LEO satellites and upper stages have been 90% successful so far.[1] Remediation of orbital debris consists of active debris removal (ADR) and to this date no ADR mission has been flown. In the same study, Liou shows that, in the assumption that the mitigation success rate is kept at 90% and ADR missions commence in 2020, at the rate of removing five large objects per year, the total number of objects in LEO would increase only slightly, from 13,000 in 2010 to 14,000 in 2210. The "business-as-usual" scenario presented by Liou, in which no ADR missions are performed and the mitigation rate is the same 90%, shows that the total number of objects in LEO almost doubles by 2210 reaching 22,000.[1]

The imaging and attitude state estimation and relative navigation algorithms developed and tested for the ARAPAIMA mission will be combined with algorithms developed by other researchers to plan maneuvers for the capture of a large space debris object such as a tumbling upper stage. It is envisioned that multiple cubesats similar to ARAPAIMA are launched by a

mother ship, they attach to the debris object, and together they gain control of the attitude of its attitude. In the next step, the cubesats perform deorbit burns and place the debris object in an orbit with a perigee sufficiently low to re-enter in a given number of years. The cubesats can ride along on the debris object to meet a fiery demise or they can return to the mother ship for refueling and maneuver to the next debris object of interest.

REQUIREMENTS

There are many different requirements from multiple sources that need to be followed during the design process of the satellite. The system's engineering team has compiled these requirements into a Requirements Verification Matrix (RVM). This is a flow down from the mission objectives and mission statements, down to the subsystem requirements. The step-by-step flow down for the ARAPAIMA mission is shown in Figure 55. The requirements are derived from the mission statement, objectives, and science. Their impact on the entire space system is traced through the flow down structure. The subsystem leads have identified their individual functional requirements, in order to accomplish the mission. Within all facets of the mission, we must conform to UNP programmatic constraint requirements, as defined in the UNP-8 User's Guide.
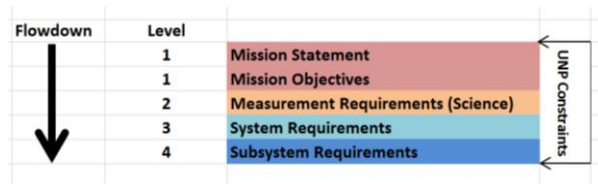

Figure 5: Mission Requirements Flow down

This matrix contains each requirement compiled from UNP, government requirements, and requirements determined by the team. The majority of the requirements are derived from the different UNP sources (UNP-8 Users Guide, UNP Expert Area Teleconferences, and other UNP documentation).

Each requirement consists of the text of the requirement, a reference ID, the method of verification, the flow down, and the justification for each requirement. The reference ID's are used to easily refer to different requirements as well as making the flow down easier to follow. There are three verification methods approved for the UNP-8 competition; testing, inspection, and analysis. These methods will describe how each requirement will be verified. Along with these methods of verification is a check mark in either a red, yellow, or green section. In the current stage of the design process, the check signifies what stage we are at

in the verification process. Red signifies the requirement is not verified, yellow signifies that some verification had begun, and green signifies that the requirement has been fully verified. The flow down shows the link from the mission objectives to the subsystem requirements. Finally, each requirement has a justification alongside it, stating why the requirement is important to include in our list. Figure 6 is a copy of the payload requirements from the RVM and demonstrates the general set-up of ARAPAIMA's requirements.

Figure 6: ARAPAIMA payload requirements

Risk Analysis

ARAPAIMA's system's engineering team has also been identifying, analyzing and mitigating mission risks. To determine the risks, the each subsystem has identified situations that could have an adverse effect on the mission. Once these situations have been identified as risks, they are evaluated and managed to ensure prevention. After risks are defined, the team analyzes and prioritizes each risk by determining the level of severity of the risk. The team is currently working on assigning numerical values to traits such as probability, impact on the mission, risk control, and effectiveness of control based off of the information in Figure 77.

Figure 7: Risk Exposure Levels

The following is an example of one of the potential risks from the payload subsystem concerning the laser rangefinder.

- Laser Rangefinder: In general, the risk associated with the laser rangefinder is a result of it not functioning properly. Since it has not, as of yet, been proven to operate in a satellite, the failure of this component is of concern. The major role of the laser rangefinder throughout the mission is to provide the point clouds required to image the satellite. The consequence of the laser rangefinder failing to operate is analyzed below in terms of the risk management process.
- The laser rangefinder fails to operate:
  - Severity: Critical (4)
  - Deciding risk criterion: Science – Critical reduction of the science return
  - Rationale: Without the laser rangefinder, the monochrome and infrared cameras will still be able to take photos of the RSO; however, the exact attitude determination of the RSO will not be able to be determined.
  - Risk treatment plan: i) Flight test the laser rangefinder through the use of the a weather balloon or similar testing.
  - Risk Factor:
    - Probability: 5
    - Impact: 7
    - Ability to control: 6
    - Effectiveness of Control: 6

After these numbers are defined, they will be used to calculate a risk factor for each risk. The team collected the numerical values from each subsystem and each potential risk was calculated using the equation shown in Equation 1 .

$$I \times P \left[\left(\frac{10-C}{10} \right) + \left(\frac{C}{10} \times \frac{10-E}{10} \right) \right] \qquad (1)$$

where I = impact, P = probability, E = effectiveness, and c = control.

The higher the risk factor, the more important it is to mitigate and mange that risk. ARAPAIMA is also in the process of determining risk mitigation. The system's engineering team conducts regular risk assessments due to the continuous evolution of our system. Figure 88 contains the most recent risk assessment the system's engineering team has completed. After each assessment, the system's engineering team looks at the risks with the largest risk factor and determines how to manage and mitigate the risk. Risks that have a low ability to control, or a low effectiveness of control, are more difficult to manage, so it us up to the team to determine which risks are able to be managed.

	Title	Severity	Impact	Probability	Control	Effectiveness of Control	Risk Factor
Power	Space debris damage solar cells	Critical (4)	8	8	1	1	63.36
Comms	Inoperable communications system because of OBC interface software failure on spacecraft.	Maximum (5)	6	8	1	5	45.6
Structures	Space debris damaging structural frame and/or solar panels	Major (3)	5	8	1	1	39.6
Comms	Inoperable communications system because of damaged feeds on spacecraft.	Maximum (5)	10	9	7	8	39.6
Payload	Monochrome camera fails to operate	Major (3)	10	5	6	6	32
Power	Batteries experiences overcharging or overheating	Maximum (5)	9	5	5	6	31.5
Power	The batteries experience high currents	Major (3)	8	5	5	5	30
Payload		Significant (2)	9	5	6	6	28.8
	IR Camera fails to operate	Significant (2) to Critical	6	5	6	2	26.4

Figure 8: ARAPAIMA Risk Assessment Table

PRIORITIZATION PLAN

Spacecraft

The subsystems of the ARAPAIMA mission have been characterized according to their impact on the mission and according to their complexity. They are presented in Figure 99. The impact is a weighted sum of the impact on the cost, budget, schedule, and technical performance. The complexity is defined in the sense of information content, as suggested by Suh. As such, a complex subsystem is one for which the information content required to satisfy its functional requirements is high.

Subsystems in the top right quadrant are the most critical ones and, accordingly, their functionality is considered highly critical. They are followed in terms of criticality by the systems in top left quadrant, which have been considered to provide critical functionality. The subsystems with medium critical functionality reside in the lower right quadrant.
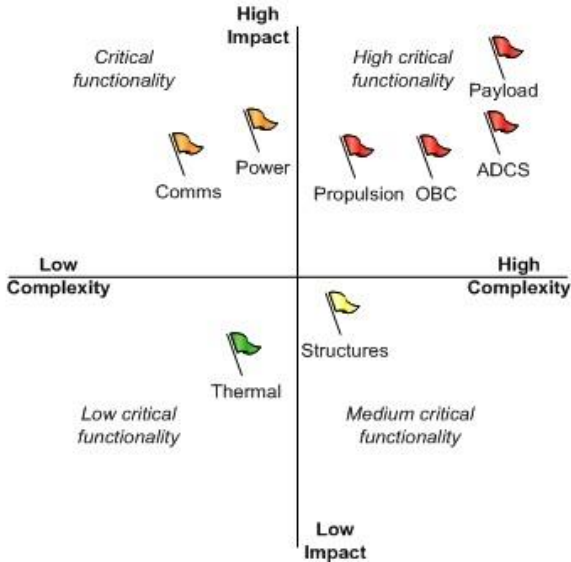
Figure 9: Subsystem Characterization

For the time being both the impact on the mission and the complexity of the subsystems are chosen heuristically, according to the team's experience and intuition. Both the impact and complexity have been further quantified in the Risk Analysis section. In addition, the results or expectations of risk mitigation measures that are proposed will also be quantified and presented in similar quadrant-chart to illustrate the progress of the design and how the design decisions mitigate the risk. After the PDR the same approach will be followed to keep track of the risk and criticality during the manufacturing and partial integration stages.

Payload Descope Plan

The payload descope plan presented here describes an initial attempt at specifying descope options. It will be revisited and updated, if needed, in the month after the SCR to quantify the impact on the mission performance and mission requirements.

The first payload component descope option is the reduction of the resolution of the visible spectrum monochrome camera. The rationale is the reduction of cost, power required, and image size. The impact is a reduction of the data that has to be stored for processing and possible downlink.

The second payload component descope option is the elimination of the payload computer and using the bus computer to run the payload science algorithms. The rationale is the reduction of cost, power and volume required. The impact is a reduction in the CPU cycles allocated to payload science algorithms and a reduction of the reliability of the overall OBC architecture.

The third payload component descope option is the elimination of the IR spectrum camera. The rationale is the reduction in cost, power and volume required. The impact is a reduction in the science to be performed, increase the risk to the mission due to the inability to observe the RSO during the eclipse side of the orbit. Imaging of the laser bloom on the RSO is also eliminated. However, the imaging of the laser bloom might be performed by the visible spectrum camera.

Spacecraft Bus Descope Plan

It is important to note that two ADCS descope options have already been exercised. They consist of the elimination of one of the two star-trackers and one of the four reaction wheels. The rationale is the reduction of cost, power, and internal volume requirements. The impact is a reduction of the reliability of the ADCS.

Prioritization of tasks: Science & Mission Imaging

Figure 2 shows the expected science Concept of Operations (CONOPS) for ARAPAIMA. Each box shown below is being developed as research code in MATLAB. It will then implemented in ANSI C for flight software and tested as part of an end-to-end payload-in-the-loop simulator, likely at the Sensor-based Control for Relative Motion (SCReAM) laboratory at AFRL's Kirtland AFB location.

Figure 1010 shows the expected descope plan for science and mission imaging, should the full development, verification and testing of all the research code required for the tasks shown in Figure 23 be infeasible.
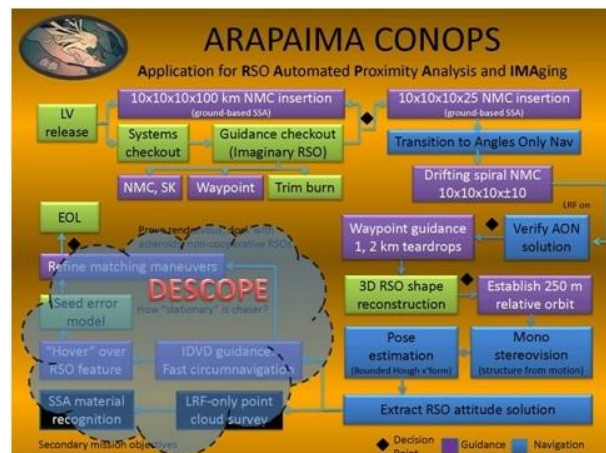

Figure 10: Descoped ARAPAIMA Science Conops

The first step of the descope plan would involve cutting development of secondary objective research to fulfill primary objectives, such as waypoint guidance development (and associated autonomous programming

conditions). Secondary objectives are still in development as part of the ARAPAIMA Experiment Plan, which will be completed by the Chief Scientist, Lt. Nayak, by Preliminary Design Review (PDR). It is expected that more secondary objectives will be added with additional collaborators / customers.

The second step of the descope plan would involve cutting development related to the objective of proving the capability to dock with a non-cooperative RSO. It is not expected that docking will occur, however, the science team would like to evaluate the pointing, guidance and navigation of the satellite with respect to a particular feature of interest on the RSO and implement a closed-loop error model to compensate for perturbations and other errors. This will allow for an evaluation of ARAPAIMA's ability to deliver products based on these highly demanding conditions. Researching, coding and testing the execution and evaluation of this final condition is expected to be highly time-intensive, and preference will be given to primary objectives if the timeline to flight software load does not permit a satisfactorily mature development. It is expected that all other science objectives shown as outside the descope cloud in Figure 10 can be completed by a January 2015 Flight Competition Review (FCR) timeline.

INTERNAL ORGANIZATION

GIT for Version Control

Currently, the science team has eleven members, all of whom are involved in various aspects of coding research code to execute various ARAPAIMA objectives. While documentation of this code can be daunting, during the development phase, version control of improved versions can be even more so. Common subfunctions, such as calculations of ephemeris, ingest of TLE, ingest of images, solar phase angle modeling, etc, are used by multiple participants, and modifications, if not tracked, could lead to a failure to compile all this work into one end-to-end mission simulator, and ultimately, into flight software.

Git is a free and open source distributed version control system designed to handle everything from small to very large projects with speed and efficiency. Git allows multiple local branches that can be entirely independent of each other. This allows the science team to perform the following:

- Context Switching. Create a branch to try out an idea, switch back to the original branch, apply a working patch, switch back to the experimentation branch, and merge it in.

- Role-Based Codelines. Have a branch that always contains only what goes to production, another that work for testing is merged into, and several smaller ones for day to day work. These have all been implemented in the ARAPAIMA Git.
- Feature Based Workflow. Members can create new branches for each new feature so the overall team can seamlessly switch back and forth between them, then delete each branch when that feature gets merged into the main ('production') line.
- Disposable Experimentation. Create a branch to experiment in, realize it's not going to work, and just delete it - abandoning the work - even if other branches have been pushed to the repository in the meantime). This frees members to try new ideas without worrying about having to plan how and when they are going to share it with others.

Overall GIT version control and branch control rests with the Chief Scientist, to allow for approval of 'successful' code as ready for on-board implementation. This is proving to be highly successful even with introducing new members to the team, as they can be allowed access to a particular branch of code, without disrupting anyone else's work, or requiring transfer of large files via email.

Conference Plan

Conferences, both national and international, present a stellar opportunity for the ARAPAIMA team to present their concepts and receive peer-review from a community involved in similar, if not identical, tasks. Publications, both in conference proceedings and technical journals, are a large part of the science team's validation of new ideas.

Figure 11 shows a list of conferences at which the team will be presenting ARAPAIMA-related research in 2013, for a likely total of ten published papers.

	Conference Name	Location	Abstract deadline	Paper deadline	Conf start	Conf end	Who's going?	No of papers
1	AAS/AIAA Spaceflight Mechanics Meeting	Kauai, HI	Passed	Passed	10-Feb-13	14-Feb-13	Bogdan Udrea	2
2	IEEE Aerospace Conference	Big Sky, MT	Passed	Passed	2-Mar-13	9-Mar-13	Jaclyn Beck	2
3	5th International Formation Flying Technologies Conference	Munich, DE	Passed	15-May-13	29-May-13	31-May-13	Mikey Nayak	2
4	Small Satellite Conference	Logan, UT	Passed	11-Jun-13	10-Aug-13	15-Aug-13	TBD	1
5	AIAA GNC Conference	Boston, MA	Passed	30-Jul-13	19-Aug-13	22-Aug-13	Jaclyn / Bogdan	2
6	Advanced Maui Optical & Space Surveillance Technologies (AMOS) Conf	Maui, HI	15-Apr-13	TBD	10-Sep-13	13-Sep-13	Mikey Nayak	TBD

Figure 11: List of conferences ARAPAIMA will be presenting in 2013

SVN for Version Control

The spacecraft team has various subsystems that require code to be written in order to meet ARAPAIMA objectives. For example, the attitude determination and control subsystem is modeling the reaction wheels using Simulink; while on-board computing is generating the code to interface with the laser range finder. As various file types are being generated and iterated it is important to have a versioning system in place. SVN is our versioning system of choice because it is directly supported by MathWorks and their Simulink Projects environment.

SVN is a universally recognized and adopted open-source, centralized version control system characterized by its reliability as a safe haven for valuable data; the simplicity of its model and usage; and its ability to support the needs of a wide variety of users and projects. Some of the key features of SVN that will be utilized by the spacecraft group are:

- Ticketing Tools. Create a work ticket for a certain file stating what it is that needs to be fixed. When the issue is resolved the ticket is filed away under completed tasks.
- Branches. Using side-line development will facilitate the creation of experimental work that could be disruptive to the trunk until it is properly tested. Branches also allow for the development of multiple versions of the same product for later evaluation and testing.
- Visual Cues. Using tags to highlight notable revisions in the history of the repository will allow for easier navigation and readability of the code base.
- Multiple Repositories. Various subsystems of the spacecraft may need to develop software that will be iterated over the lifetime of the project. By allowing each subsystem to have a repository the code base will not be overbearing.

Version control of the trunk (main branch) of development will be in control of each subsystem lead. Experimental branches can be used by anyone looking to further develop the software without worrying about breaking the trunk. Once experimental code becomes mature enough the subsystem lead will have the ability to merge the branches.

Assigning Tasks

Ensuring that tasks are assigned to the proper groups as quickly and efficiently as possible helps to keep the project moving forward in a unified direction. The web service Evernote is a critical part of issuing and prioritizing tasks. Each of the ARAPAIMA subsystems has a premium Evernote account that allows the sharing of notebooks. The "ARAPAIMA Program Management" notebook contains a to-do list note for each subsystem. The program manager, systems engineers, and subsystem team leads add tasks to the to-do lists. The standard format for writing to-dos denotes the importance level (critical, uncritical), priority (urgent, not urgent) and the due date for each task. Once a task is completed the to-do is checked off and a line is added indicating the person who completed the task.

In order to ensure that tasks are being placed in their proper locations, and with the correct importance and priority levels, the project manager, systems engineers, and principle investigators share a notebook where ideas can quickly be added and don't require the same structure as the program management notebook. Additionally, every week there is a subsystem team lead meeting including the project manager to discuss tasks completed the previous week, and to assign new tasks for the upcoming one.

File Naming Convention

A standardized file naming convention is an efficient and practical method of maintaining documents, files, and folders. The web service Dropbox is the main method for saving any and all pertinent files. Every member participating in the ARAPAIMA project has access to the shared ARAPAIMA folder within the Dropbox web service. The file naming convention is outlined below.

- (Subsytem abbreviation)(Three digit code)-(Descriptive Title)
- E.G. "SUB100-Example"
- All spaces between words are denoted by an underscore to ease use on Linux-based computers
- All documents (Word and Excel) have a table of revisions with the following fields:
  - Revision number
  - Description of changes made
  - Date of the change
  - Initials of approval from superior

This system was inspired by ARMADILLO (The University of Texas at Austin)

The file naming convention is outlined further in Figure 12. Here it shows the breakdown of what type of documents to expect for each three-digit code.
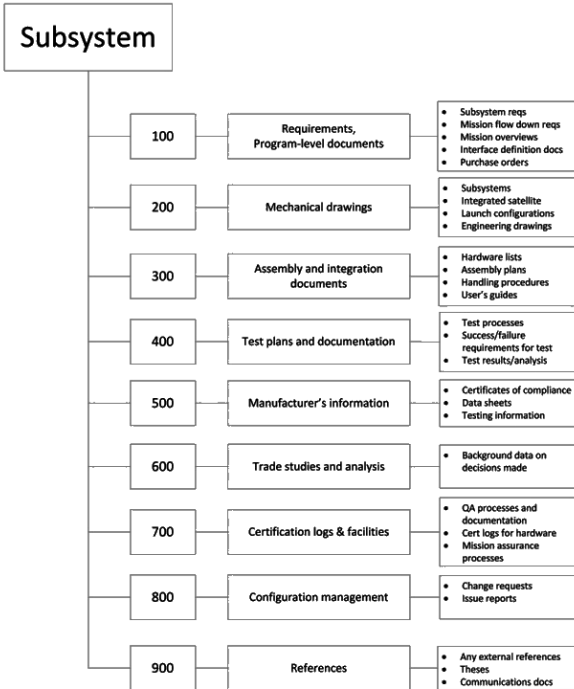
Figure 12: The documentation plan structure for file naming

In the three-digit code for the naming convention, the second and third numbers are determined by the spacecraft component that the document is referring to.

Figure 13: Spacecraft component identification numbers

The numbering convention is called the spacecraft component identification number. This list of numbers is developed along with the spacecraft as more components are researched and added to the design. An example of the numbering convention for some of the components used in ARAPAIMA are shown in Figure 133.

INTERNAL REVIEWS

Spacecraft

The team is actively recruiting members of for its Advisory Board from the space industry and government organizations that conduct space related research and development. Experts are sought from all branches of space mission design. Once the Advisory Board is mobilized its members will be asked to advise in the design of the spacecraft subsystems and review design decisions taken by the team. The members of the Advisory Board will be provided with draft review presentations and review reports in a timely manner to allow for feedback prior to release of the documents to the UNP PO.

In addition to the experts of Advisory Board, which are all external to the both ERAU and U of Ark, the team will engage with faculty at the respective campuses with either advising students or direct contributions to the ARAPAIMA research and development effort. At ERAU Prof. Hamilton Hagar is currently engaged in advising the ARAPAIMA System Engineer Lead with the derivation and traceability of the requirements, Prof. William Barrot is advising the Communication Subsystem Lead with the radio communication system design and link budget analysis, Prof. Marc Compere is advising the Power Subsystem Lead with the development of the requirements and preliminary power budget analysis, and last but not least Prof. Peter Erdman is advising the Payload Engineers in the design and specification of the requirements for optical assemblies and IR camera.

The ARAPAIMA mission has intimately linked with the Spacecraft Design courses (AE427/AE445) at the ERAU Aerospace Engineering Department during the 2012-13 academic year. The current team is transferring the leadership and technical expertise to a set of volunteers whom will work outside of the design classes. It is expected that during the 2013-14 the ARAPAIMA project will be decoupled from the Spacecraft Design courses but top performing students will be recruited for ARAPAIMA work.

An additional form of peer and community review of the ARAPAIMA work is pursued by attending conferences and possibly publishing papers in peer reviewed journals. The conference papers either presented or in progress are shown in Figure 14.

#	Paper Title	Conference	Date	Status
1	Application of a Laser Rangefinder for Space Object Imaging and Shape Reconstruction	2013 AAS Space Flight Dynamics Conference	Feb 10-14, 2013	Presented
2	Experimental Characterization of a Miniature Laser Rangefinder	2013 AAS Space Flight Dynamics Conference	Feb 10-14, 2013	Presented
3	Design of Relative Motion and Attitude Profiles for Three-Dimensional Resident Space Object Imaging with a Laser Rangefinder	2013 IEEE Aerospace Conference	Mar 2-9, 2013	Presented
4	Real-Time Attitude Commanding to Detect Coverage Gaps and Generate High Resolution Point Clouds for RSO Shape Characterization with a Laser Rangefinder	2013 IEEE Aerospace Conference	Mar 2-9, 2013	Presented
5	Mission Design and Concept of Operations of a 6U CubeSat Mission for Proximity Operations and RSO Imaging	5th Intl. Conference on Spacecraft Formation Flying Missions and Technologies	May 29-31, 2013	Presented
6	Application for RSO Automated Proximity Analysis and IMAging (ARAPAIMA): Development of a Cubesat-based Space Situational Awareness Mission	SmallSat Conference 2013	Aug 10-15, 2013	Abstract accepted
6	Payload and AOCS of a 12U Cubesat for Asteroid Scouting	2013 AIAA GNC Conference	Aug 19-22, 2013	Abstract accepted

Figure 14: Conference papers related to the ARAPAIMA mission

Science

Weekly status reviews are conducted with the Chief Scientist, Lt. Nayak, to ensure that all team members are staying on track with assigned objectives. A high-level Microsoft Project schedule is used to map research objectives to flight software needs, via the high-level CONOPS diagram.

Conference peer review and the paper submission process present an excellent opportunity for team members to exercise research rigor and method documentation. As seen in Section 9, the Science team plans to use the conference and journal process as an integral part of the creation and validation of ARAPAIMA-ready flight software.

PERSONNEL BUDGET

Responsibilities of student team and subsystem leads

Each subsystem has specific responsibilities that will help them accomplish their goals. The power subsystem is required to create the power budget, define battery and solar panel specifications, and determine the power board components that will be used. Attitude, determination, and control subsystem will be responsible for simulation modeling, writing technical specifications, and defining reference frames. The payload subsystem will design and manufacture components, test the payload, and validate their tests results. The communications subsystem will define a link and data budget, and create antenna, radio, and ground station specifications. The structures subsystem will provide CATIA designs, structural finite element analysis, and rapid prototyping. The thermal subsystem will perform thermal analysis and define satellite safeguards. The OBC subsystem will test their components, select hardware and software to be used, and create accurate interfacing.

Propulsion Subsystem

The ARAPAIMA propulsion system is being developed in-house at the University of Arkansas's Mechanical Engineering Department. The personnel of this subsystem is drawn upon mainly from the members of the UA American Institute of Aeronautics and Astronautics (AIAA) Student Chapter and from the students interested in the space hardware design for their ME senior capstone (MEEG-4131, -4133; two semesters). The UA ME Department currently includes a student body of approximately 500 undergraduate students, including declared freshmen class of 2012-13.

The UA ARAIPAIMA propulsion team is expected to consist of students with ranks from freshmen to senior. The team is currently recruiting students, starting with senior capstone students and then followed by voluntary students of lower ranks. The Propulsion System Lead is Zachary Callahan. Mr. Callahan is currently a 3rd year senior-rank student completing his core ME curriculum (statics, dynamics, materials, mechanics of materials, numerical methods, thermodynamics, fluid-mechanics, heat-transfer, machine analysis/design, electronics, and ME labs). Complementing them are his hands-on extracurricular experiences from the summer Research Experiences for Undergraduates (2012) and current position as a UA Honors College research student, providing the technical leadership and management of the ARAPAIMA propulsion system team. Ideally, each subsystem should be managed by students (5 members) with similar curricular experiences as Mr. Callahan; however, it can be further delegated to lowerclassmen such as freshmen (CAD), sophomore (materials, analysis), junior (manufacturing).

Identified Gaps in Personnel/Expertise

As a team we demonstrate expertise in many different software packages such as Microsoft Office, Visio, MATLAB, CATIA V5, Systems Tool Kit (STK), Nastran, and Simulink. These qualifications were acquired through industry experience, class projects, and technical club involvement. Team members are also expected to be able to think critically and solve technical challenges.

SUBSYSTEM PROGRESS

Attitude Determination and Control

Since inception, the ADC team has been working hard researching and implementing the attitude dynamics of a satellite in low earth orbit. External and internal torques have been derived and simulated to better the accuracy of the model. Recently, preliminary controller design to satisfy pointing requirements has started. The

pointing requirements include and knowledge accuracy of at least 1 arcminute during the science mode and a control accuracy of at least 2 arcminutes during the science mode.

The modeled disturbance torques include aerodynamic, gravity gradient, residual magnetic moment, solar radiation pressure, reaction wheel imbalance, propellant slosh, solar panel vibration, and orbital maneuver thruster misalignment.

Future designing and testing will ensure our ADC algorithm will continue to deliver the required attitude for all operational modes during the actual mission.

Communications

The radio for the nanosat has been selected and in the process of being purchased. The architecture of the communications system is shown in Figure 155 with the chosen components noted. The link budget is completed and has identified the type of antennas needed to have proper communication between the ground station and the nanosat. Testing of the placement of the antennas are currently in progress.
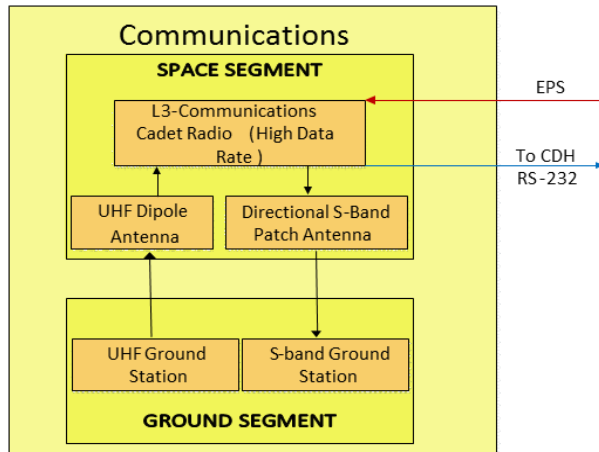

Figure 155: Communications architecture

The analysis for the communications system using the link budget resulted in the values shown in Table 1.

Table 1: Communications analysis values

Frequencies	Uplink	450 MHz (UHF)
	Downlink	2.25 GHz (S-band)
Uplink Budget	Carrier to Noise Ratio	54.58 dB-Hz

	Data Link Margin achieved	9.03 dB
Downlink Budget	Carrier to Noise Ratio	71.19 dB-Hz
	Data Link Margin achieved	6.35dB

Electrical Power System

The power subsystem has made significant progress since the beginning of the project. Early on the satellite modes were established, a preliminary STK analysis for power acquisition was constructed, and a preliminary power budget was produced. As the project matured so did the power budget, as well as the need to do preliminary testing of the power consumption of the individual subsystems. The block diagram for the power subsystem describes the flow from the solar panels through to each spacecraft component and is shown in Figure 166.
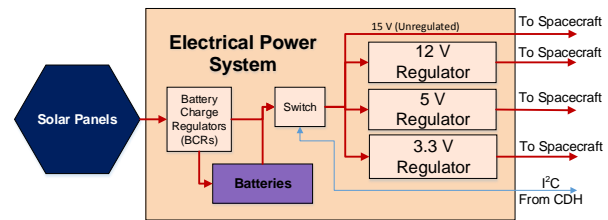

Figure 166: Electrical Power System Block Diagram

The power budget has allowed for the determination of the power consumption of the spacecraft. The peak power for the spacecraft is 126.23W and the average power is 25.60W; whereas the orbital energy is 148901.95J.

Most recently we have constructed breadboard models emulating the components of their respective subsystem and we have started some preliminary testing to ensure the power subsystem can adequately sustain the entire system.

On-Board Computer

The On-Board Computing (OBC) team has, in the course of the project, designed both the main computer and payload computer for the ARAPAIMA satellite and an interface method between the computer and the various subsystems. The software for the computers is Real-time Linux OS with custom JAVA based system control software. The overall software architecture can be seen in Figure 177.

The OBC team has also finished construction of the payload computer, and has nearly finished the creation of the payload computer software, which will allow a simple interaction between ground station and satellite. Testing has also been done to ensure that the payload computer can handle all data processing and command tasks required of it.
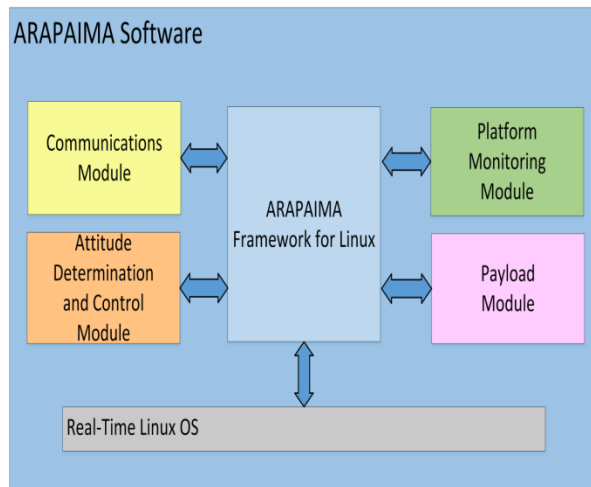

Figure 177: ARAPAIMA software architecture

Payload

In the design of the project, the payload subsystem has taken many steps toward designing, integrating, and testing the payload components for the nanosat. Each of the components for the payload have been selected and are starting to be purchased. Testing has been completed using an emulator of the payload components, this testing has allowed us to identify where we need more information and the success with which the components work together. In the near future, further testing will be completed to test the payload with moving targets and test the fidelity of the written algorithms.

The results of testing on the laser rangefinder allowed for error characterization for the laser rangefinder modeling in the algorithms. The modeling includes errors caused by pulse dilation and the influence of the material reflectance on the readings. One of the many graphs of the results is shown in
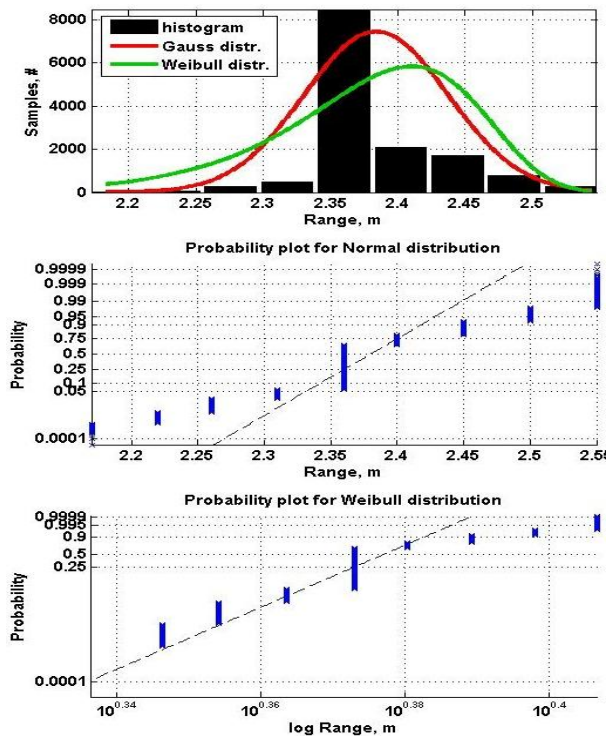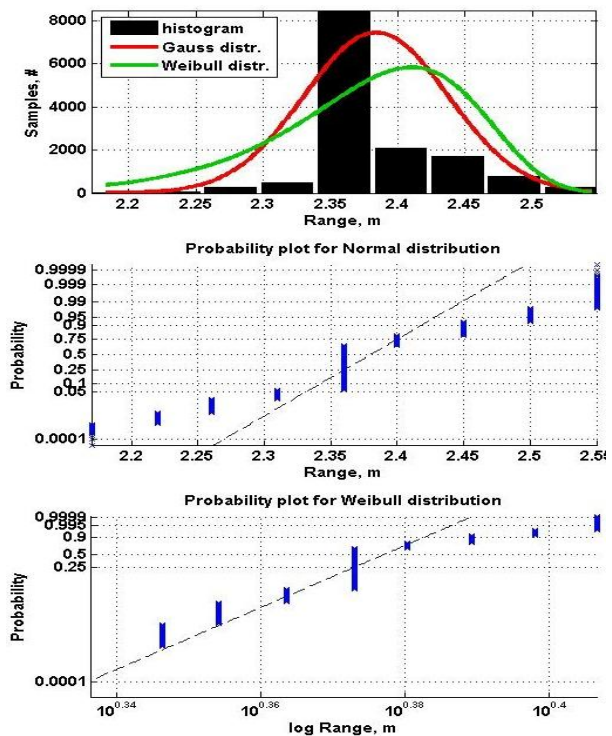

Figure 188.

Figure 188: Laser rangefinder testing results

Propulsion

Throughout the progress of the project the propulsion subsystem has focused on three areas: propellant tank design, propellant delivery system design, and the

valve/nozzle design. At this point they have a working propellant tank design which serves the dual purpose of propellant reservoir and structural reinforcement for the satellite's chassis. The propellant delivery system is less definite since it depends on the placement of other hardware within the body, but a generic pipe and connector design is ready and awaiting modifications. Finally, the valve design has been the subsystem's main focus; it consists of a working valve driver circuit design, a prototype communication or logic board, and a system of solenoid valves. The design makes good use of the satellite's space and power supply. It is also flexible enough to allow for different valve models or propellants to be tested once the hardware has been assembled.

The current specifications for the propulsion system include using HFC-236fa with an I_{sp} of 47s along with a 500mN orbital maneuver thruster, and 8 10mN RCS thrusters. The propulsion diagram is shown in Figure 19.
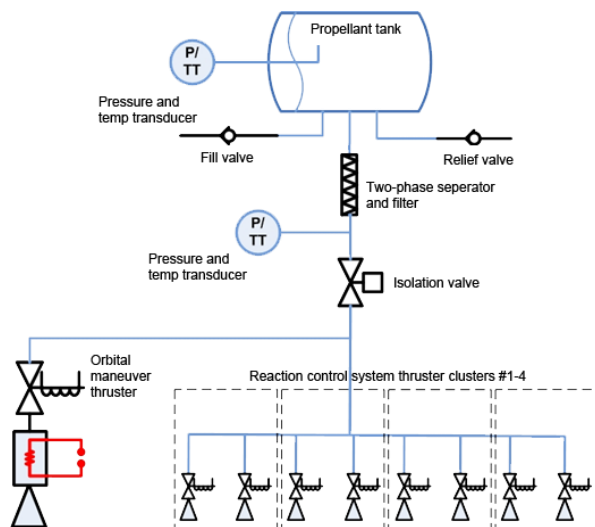

Figure 19: Propulsion system diagram

Structures

In the design of the structure there were many issues to consider. To begin, there was no heritage design to go from, so we decided to make the structure as simple in robust as possible. Therefore we made the baseplate thicker than the rest of the structure it would take the most loading and also incorporated the rails that are attached to the CSD. To achieve this we did a lot of FEA with Femap/NeiNASTRAN as well as CATIA V5 to simulate the loads that might occur during flight. We also model the structure in CATIA which then we were able to rapid prototype it using our 3D printer. This allowed us to make sure that all the components fit together nicely.

One of the first finite element analysis (FEA) that we performed was 400N to the –Z face because that is the force which is imparted by the CSD ejection plate during launch due to vibration. As seen below in
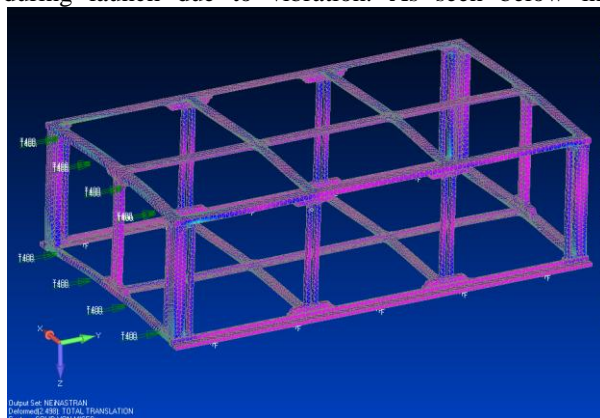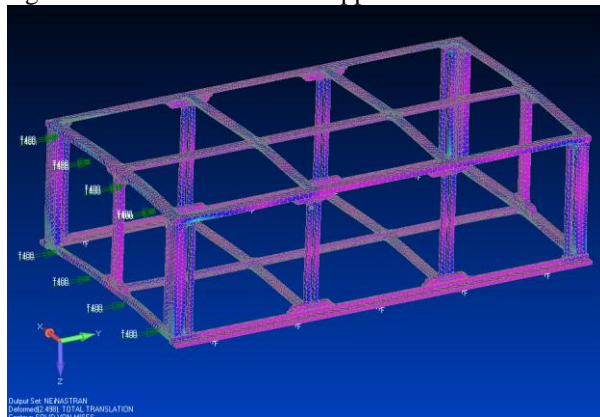

Figure 20: FEA of 400N applied to the -Z face

Figure, our structure had a displacement of 2.498 mm shown in the bottom left corner. Our next FEA was to apply the max amount of gravitational forces that the cubesat may encounter during launch in the Titan IV. Based on the Mass Acceleration Curve (MAC) of Titan IV and the maximum mass constraint, 12kg, of our 6U cubesat we approximated that it would undergo 20g's of force.
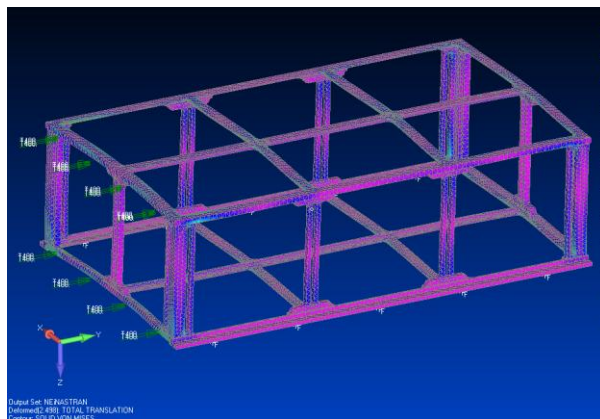

Figure 20: FEA of 400N applied to the -Z face

Figure shows 2352N or 20g's of force being exerted on the top plate of the cubesat. The deformation was calculated to be 71.94 mm, this is a big deformation for the satellite but this analysis is only for the chassis. The propellant tank, which is located in the 2 middle units, and trays, containing the payload, act as secondary supports and help the structure maintain its integrity.
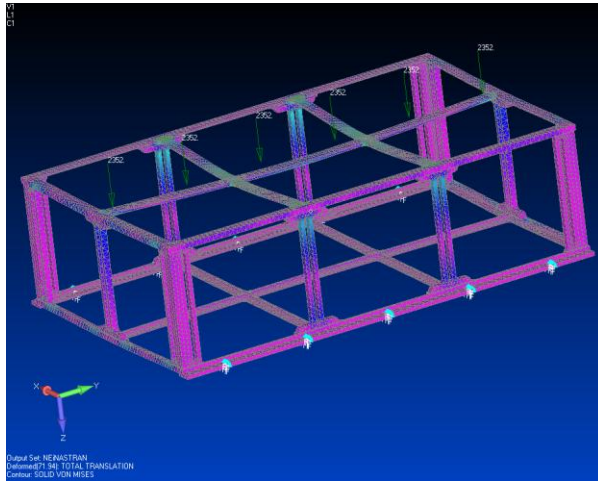

Figure 21: Top plate undergoing 2352N

The current structure and components can be seen in .

Systems

The System's engineering subsystem of the team has been an important part of the design process of the nanosat. Compiling, organizing, verifying and providing justifications for the requirements ensures that the design will meet all UNP standards. Risk analyses have been completed in order to mitigate and manage any potential risks that can go wrong, increasing the likelihood for success in the mission. Regular upkeep of the mass, data, and cost budgets have ensured that the nanosat stays within the teams budgets. In the future, regular upkeep and adjustments to the requirements, risk analysis, and budgets will be done to stay current with the design.

Thermal Control System

The thermal subsystem has learned much in the past year about the 4 modes of operation and their importance in ensuring the survival of our satellite. In the past few months, we've researched and sought after an understanding of the many variables that are associated with the operation of our satellite such as the view factor, the different types of radiation, the thermal equilibrium equation, the fluctuating Albeado and IR

values, etc. Using the information we found, we performed a static analysis of the satellite and determined the hot and cold cases for a one node and six node rectangle which haven't been documented in an Excel spreadsheet. The most exciting thing about the results we received from the six node rectangle is the fact that the range falls in a previously estimated range from about a year ago, which ensures our team that we are the right track. The biggest thing we are going to focus on in the next few months is the double-digit node analysis, transient analysis and the integration of the software ESATAN and NASTRAN in our analysis, and we are hoping for continued consistency in our data.

The single and 6 node analysis performed on ARAPAIMA used a rectangular shape without the solar panel configuration. The satellite was examined using extreme IR and Albeado values, resulting in a hot case of ~85° ± 1°C and a cold case of ~11° ± 1°C with a 11°C margin.

CONCLUSION

The ARAPAIMA cubesat is currently at a preliminary design review level. Currently, most of the subsystems and budgets are at a level from which we can proceed with detailed design and give us confidence for a good design at the critical design review.

ACKNOWLEDGEMENTS

REFERENCES

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